Euler-Euler Modeling of Mass-Transfer in Bubbly Flows

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Overview

- Motivation and Goal
- Baseline Model for Fluid Dynamics
- Including Mass Transfer
- Summary and Outlook

Reaktive Blasenströmungen
DFG SPP 1740

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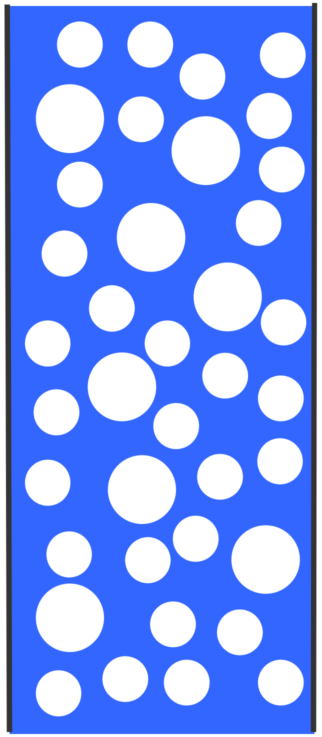
Two different perspectives on multiphase flow



→ **Averaging** →

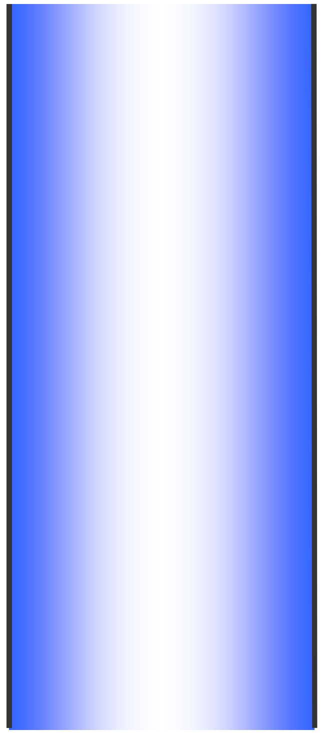
eliminiates small scales

thus

lower resolution suffices

but

closure models required



Interface Dynamics:

at each position

either gas or liquid

Two **F**luid **M**odel:

both gas and liquid everywhere

with certain probability

Motivation & Goal

- Simulation on **industrial scale** is feasible with Two-Fluid-Model

  but needs development of **closure relations**.

- To **predict** phenomena for a certain range of conditions

  models must work **without adjustments**.

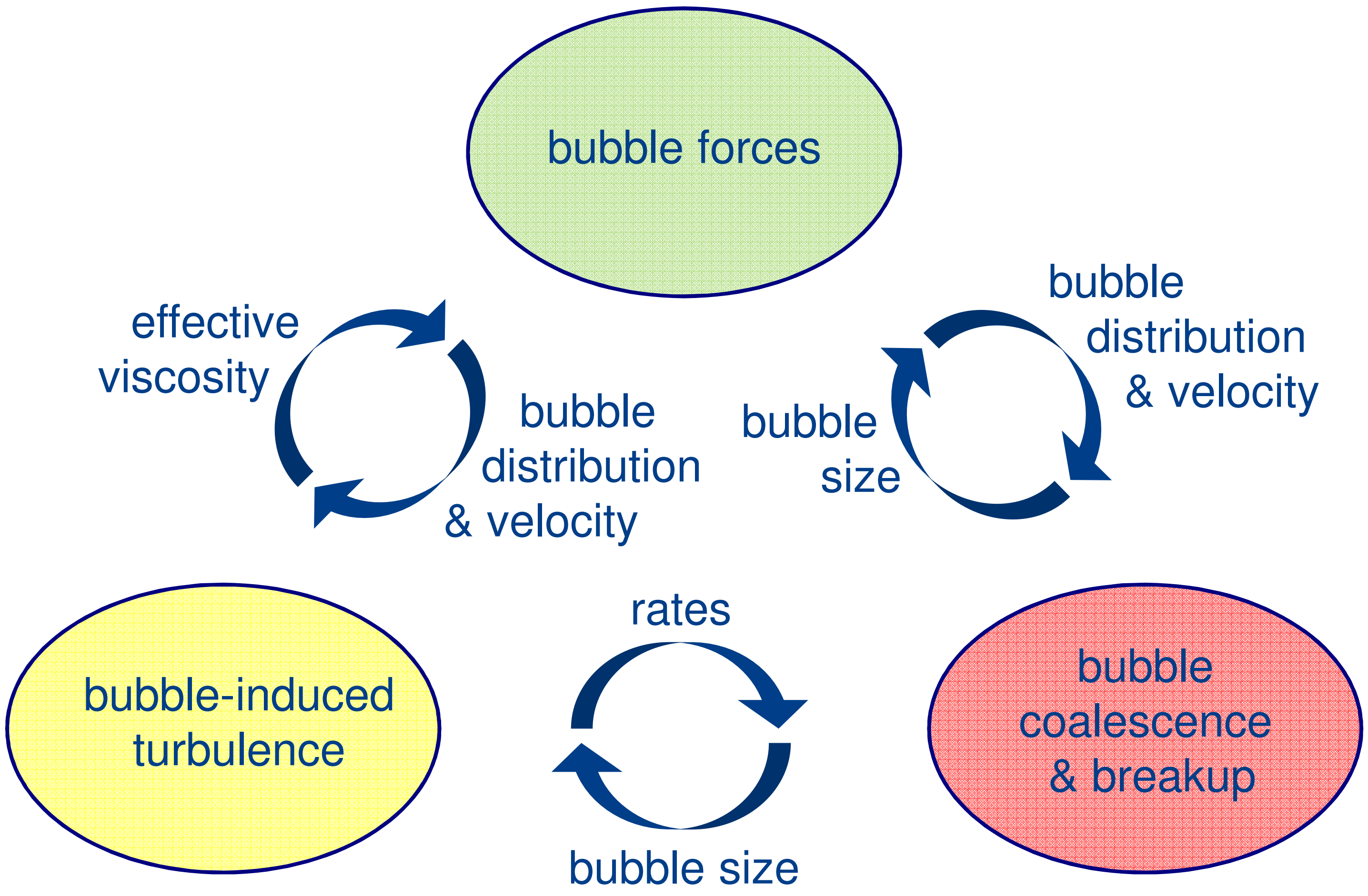
- **Same closures** should work for all systems

  with **same physics** at the bubble scale.

- **Baseline model** provides starting point

  further development **expands** range of applicability and accuracy.

Closure is a very complex problem

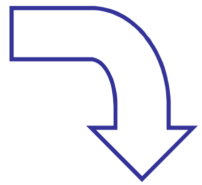


… without claiming completeness

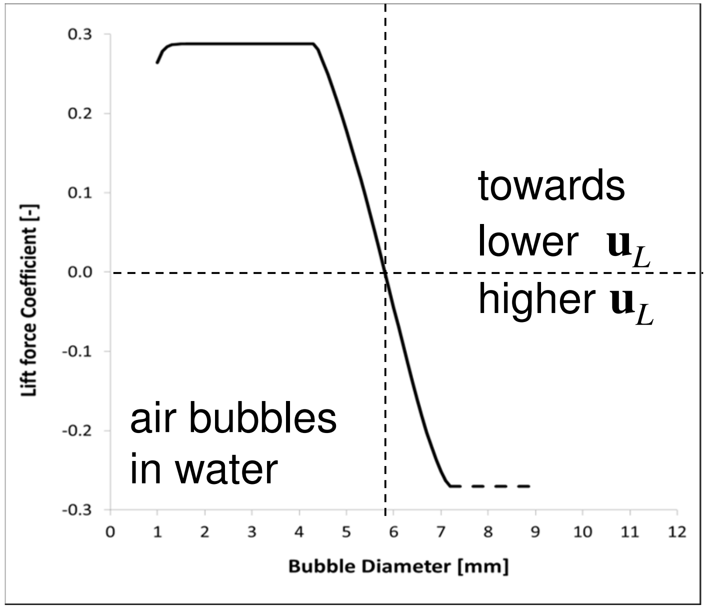
Bubble Forces

- drag [1979_Ishii]
- (shear) lift [2002_Tomiyama]
- wall (lift) [2002_Hosokawa]
- turbulent dispersion [2004_Burns]
- virtual mass $C^{VM} = 1/2$

$$\mathbf{F}^{lift} \propto \nabla \mathbf{u}_L$$



$$\mathbf{F}^{disp} \propto -\mu_L^{eff} \nabla \alpha_G$$



- largely based on experiments with single bubbles in laminar flows

Turbulence

- liquid phase only
  - shear-induced → SST model like for single phase flow
  - bubble-induced → source terms for k and ε / ω

- k-source: power transferred to liquid by drag

$$S_L^k = \mathbf{F}_L^{drag} \cdot \left| \mathbf{u}_G - \mathbf{u}_L \right|$$

- ε-source: dimensional argument similar to single phase case

$$S_L^\varepsilon = C_{\varepsilon B} \frac{S_L^k}{\tau}$$ (transformed to ω)

- τ and $C_{\varepsilon B}$ from trial and error

$$\tau = d_B \big/ \sqrt{k_L} \qquad C_{\varepsilon B} = 1.0$$

- no extra contribution needed in effective viscosity

$$\mu^{turb} = \rho\, k \big/ \omega$$ (% limiter)

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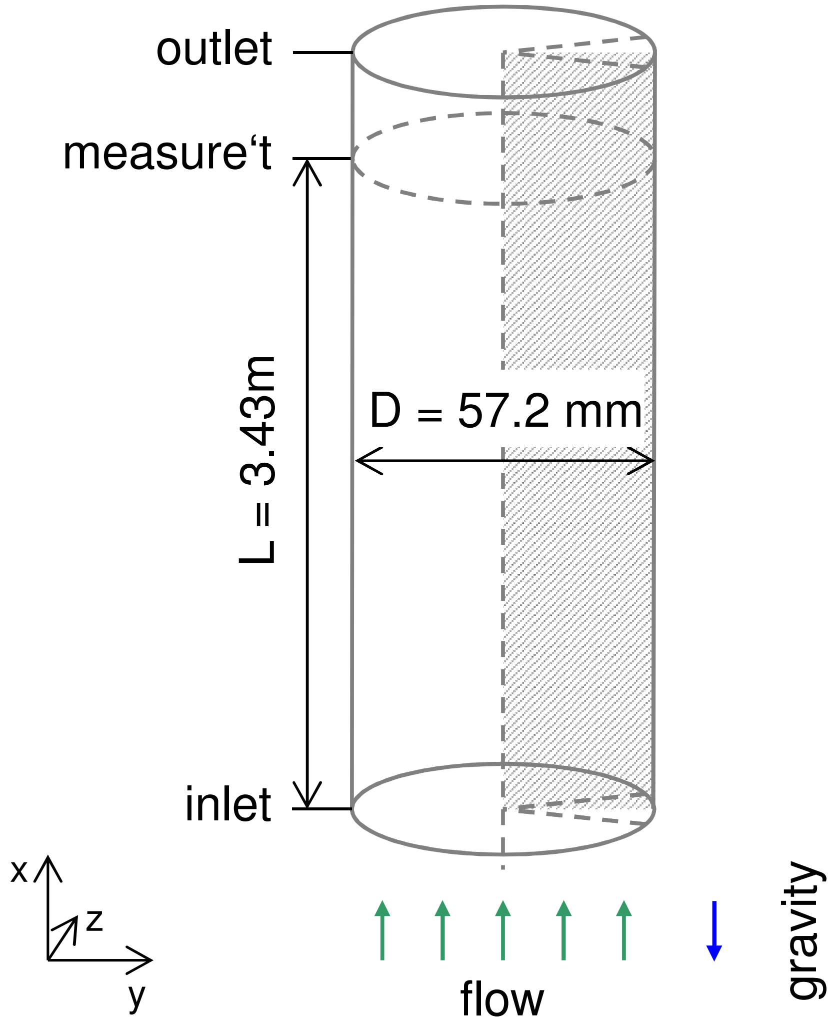
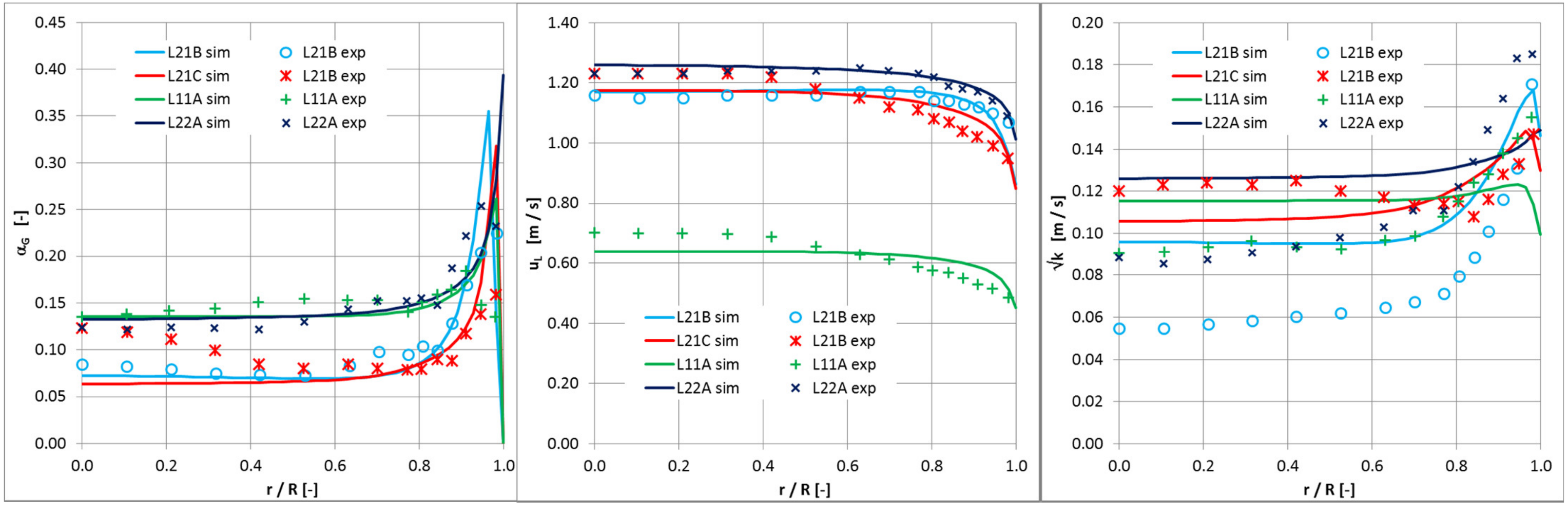
Pipe flow [1998_Liu]

- stationary simulation
  of narrow pipe sector
  valid for axisymmetric flow
- assuming monodisperse
  bubble size distribution
  taken from measurements
- fully developed conditions
  at measurement level
- uniform gas profile at inlet
- air bubbles in water (P = 1bar)



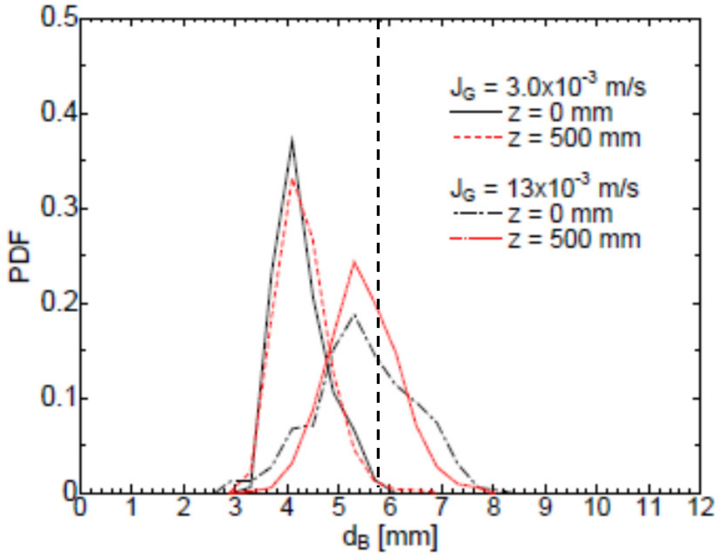
Results



- void fraction: good in center, wall peak too high
- liquid velocity: quantitative deviations small, but too steep near wall
- turbulent energy: too high in center, too low near wall
- exception: double peaked profile

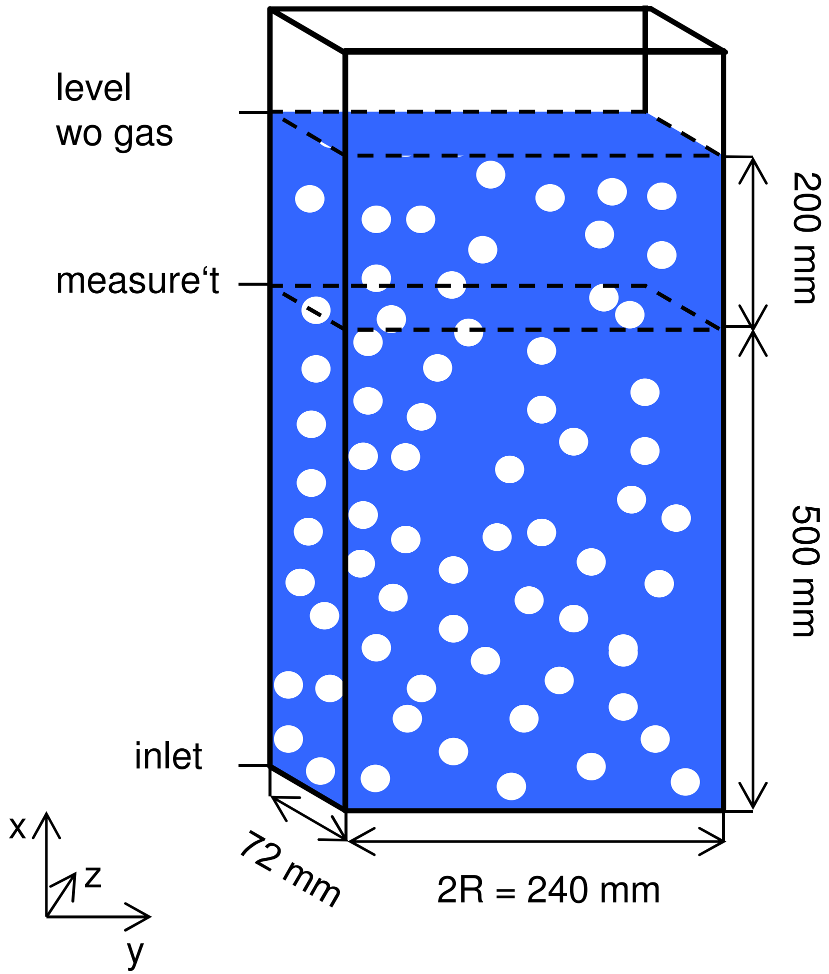
Bubble Column [2012_Akbar]

- 3D transient simulation (URANS)
- with fixed polydispersity taken from measurements
- 1 or 2 MUSIG groups
- individual nozzles at inlet
- air bubbles in water (P = 1bar)



(b)

Figure 3 Bubble images taken at $z = 0$ and 500 mm and bubble size distributions



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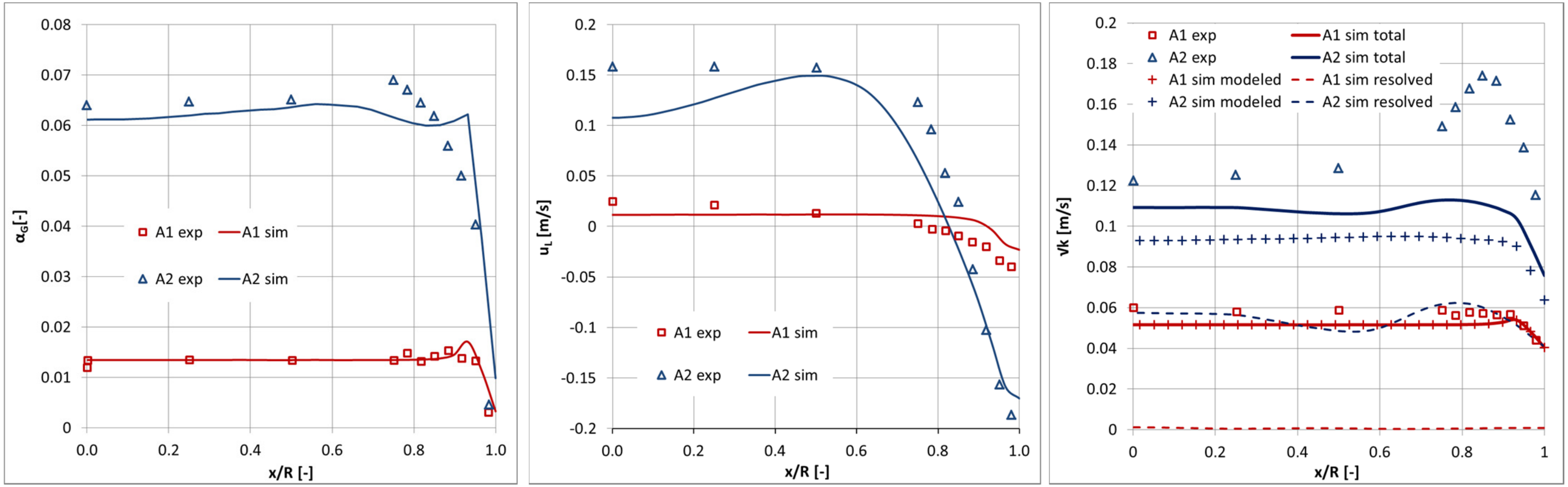
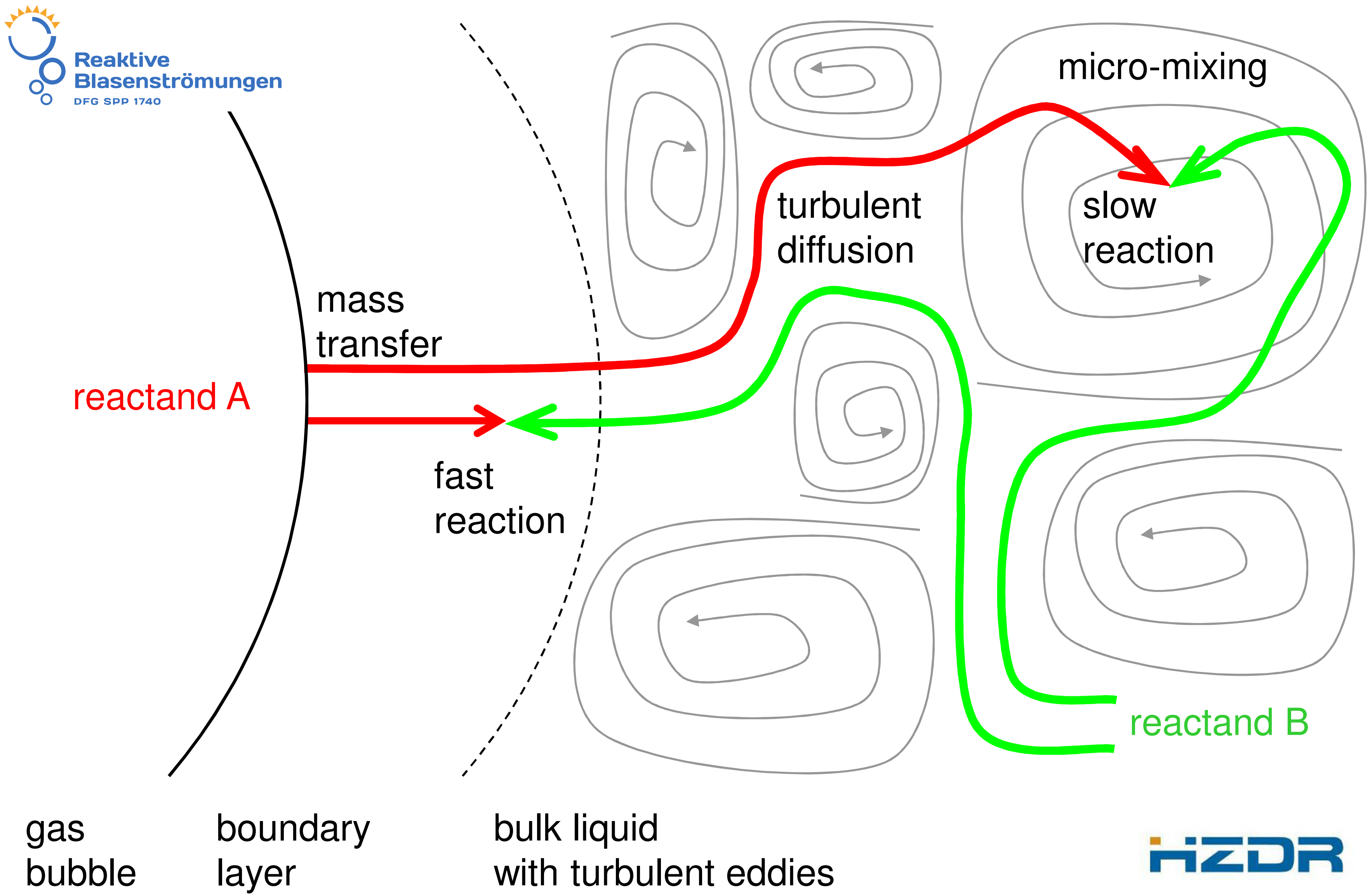
Results

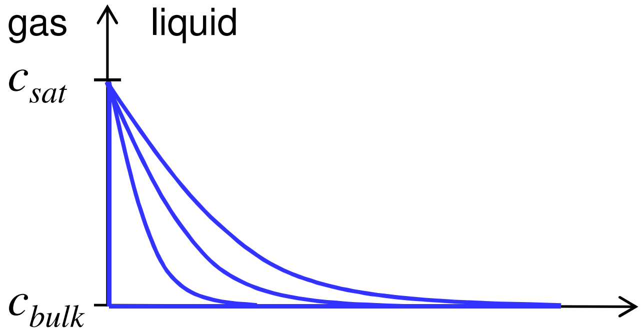


- void fraction: quantitative deviations small, but too peaked near wall
- liquid velocity: zero-crossing at different position, dip in center
- turbulent energy:
  - too low on average, peak near wall missed
  - modeled contribution dominant

Processes involved in reactive mass transfer



Mass Transfer Coefficient



- penetration / renewal model
- good for thin concentration boundary layer
- transient diffusion in plane geometry

- time-averaged mass transfer coefficient

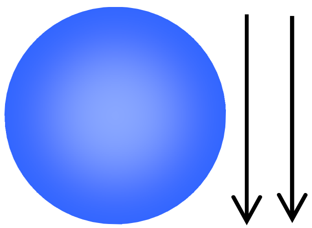
$$k_L \propto \frac{2}{\sqrt{\pi}} \left(D_L \tau_c^{-1} \right)^{1/2}$$

- **big question: What is the contact time τ_c ?**

- three answers:

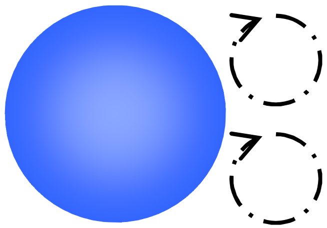
laminar model [1935_Higbie]

$$\tau_c^{-1} = \frac{u_{rel}}{d_B}$$



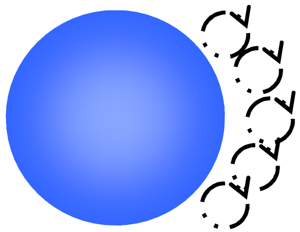
large eddy model [1967_Fortescue]

$$\tau_c^{-1} \propto \frac{\varepsilon_L}{k_L} \propto \frac{\Lambda}{\sqrt{k_L}} \propto \frac{\sqrt{2}\ \varepsilon_L^{1/3}}{\Lambda^{2/3}}$$



small eddy model [1970_Lamont]

$$\tau_c^{-1} \propto \left(\frac{\varepsilon_L}{\nu_L} \right)^{1/2}$$

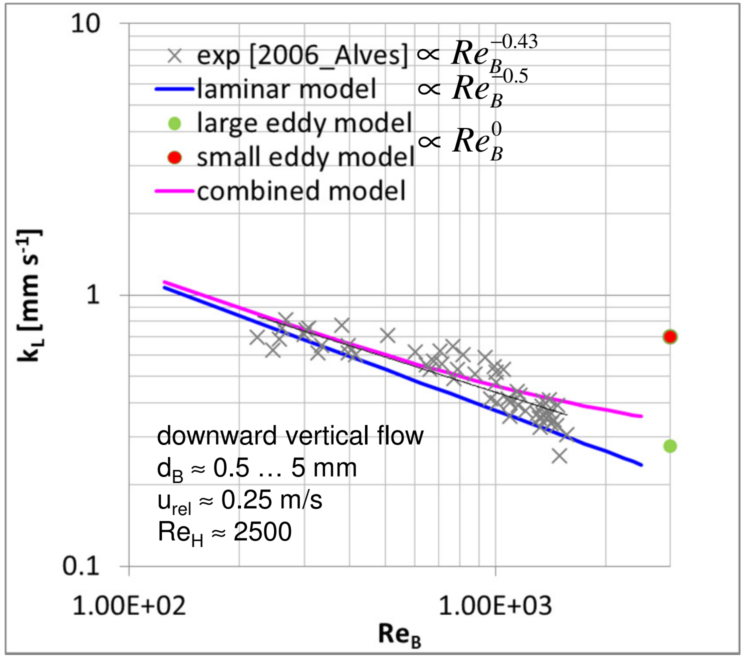


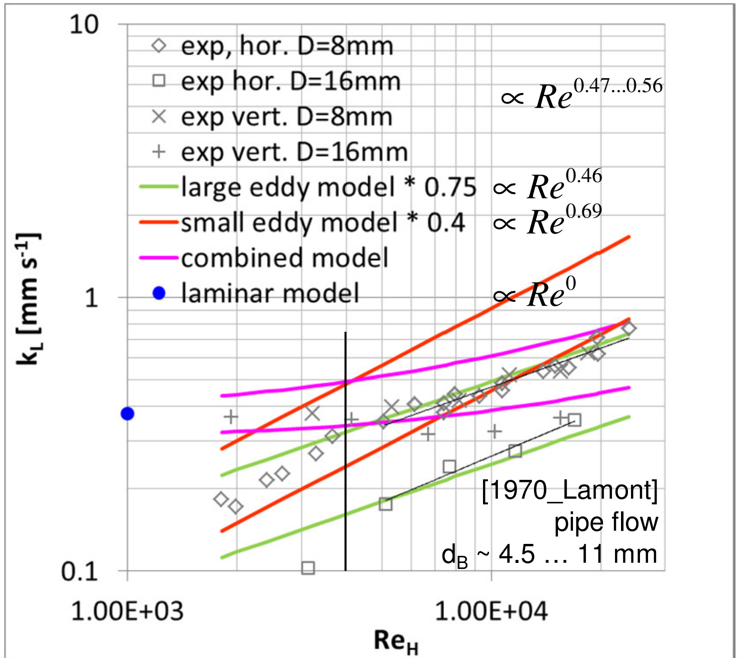
Mass Transfer Coefficient

- **Which answer is correct ?**

- qualitative evidence
- laminar model: numerous investigations on
  - bubbles rising in quiescent flow
- eddy models: situations where
  - u_{rel} is 0 like in horizontal bubbly flow
  - d_B tends to ∞ like in open channel flow

- quantitative analysis of available data
- laminar model:
  - still good for moderate trubulence
- eddy models:
  - favor large over small eddy model
- combined model:
  - tentatively add inverse contact times





Mass Transfer Coefficient

- **needs for better understanding!**

- laminar model:
- include effects of bubble shape, path, oscillation, wake

- turbulent models:
- consider spectrum of eddies
- needs good model for bubble induced turbulence

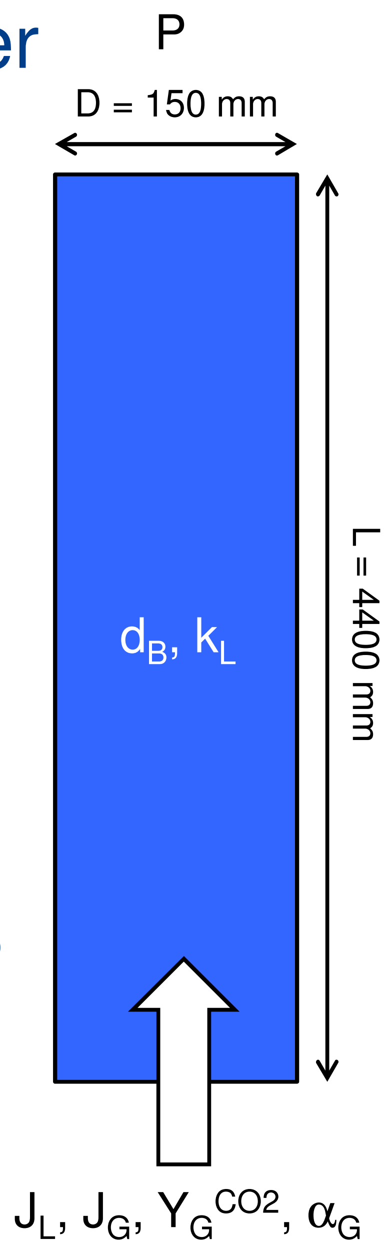
- unite both mechanisms

Euler-Euler Simulations with Mass Transfer

- literature: validation only by integral quantities,
  e.g. integral $k_L a$-value total gas holdup
- needed: validation using local information,
  e.g. axial profiles of gas fraction and concentration

- [1978_Deckwer]:
  cocurrent absorption
  of CO2 from air bubbles into water
  in a bubble column

- peculiar: mean bubble size does not change
  → bypass modeling of bubble coalescence and breakup
  → use constant k_L obtained from the data



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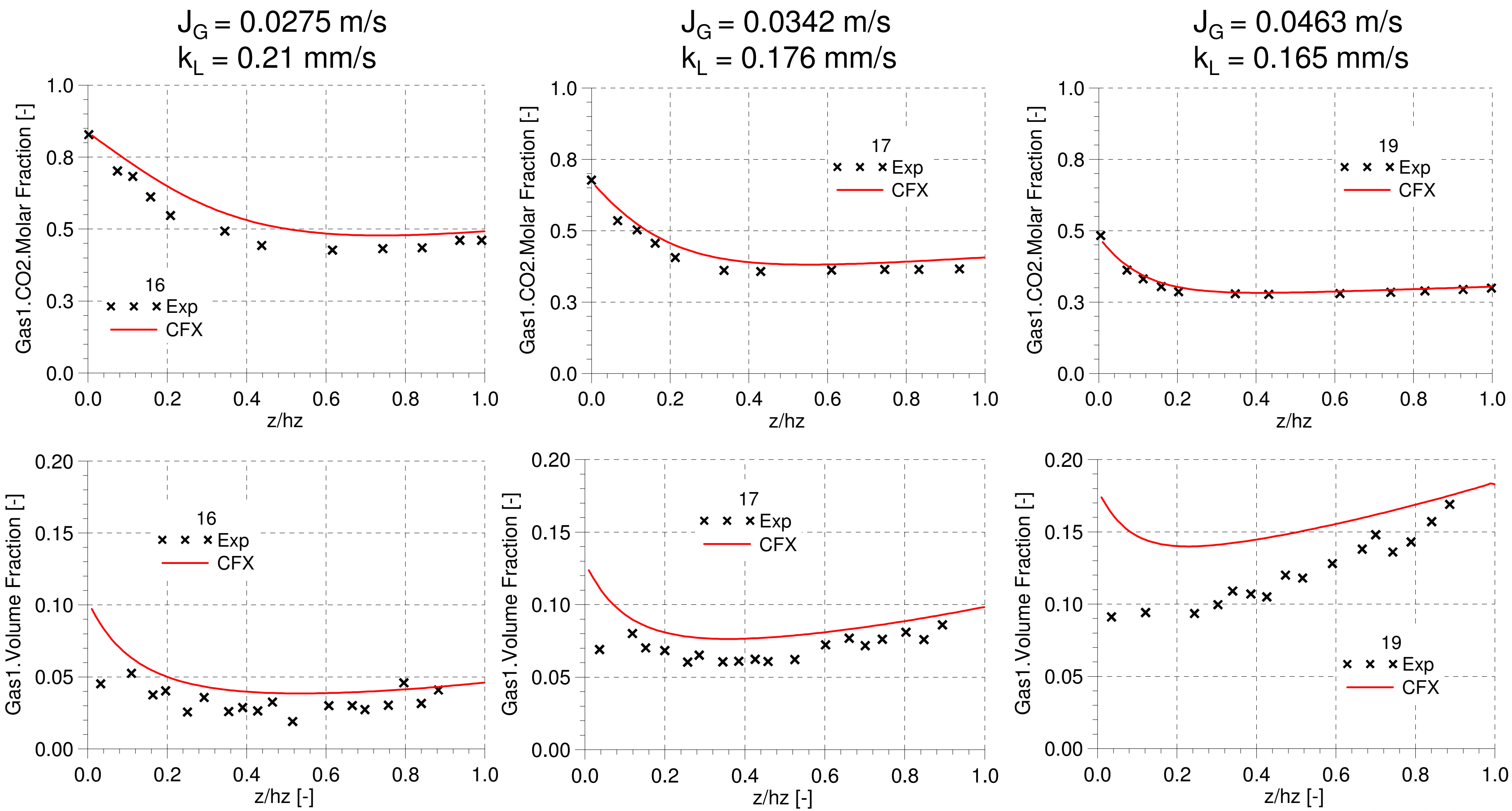
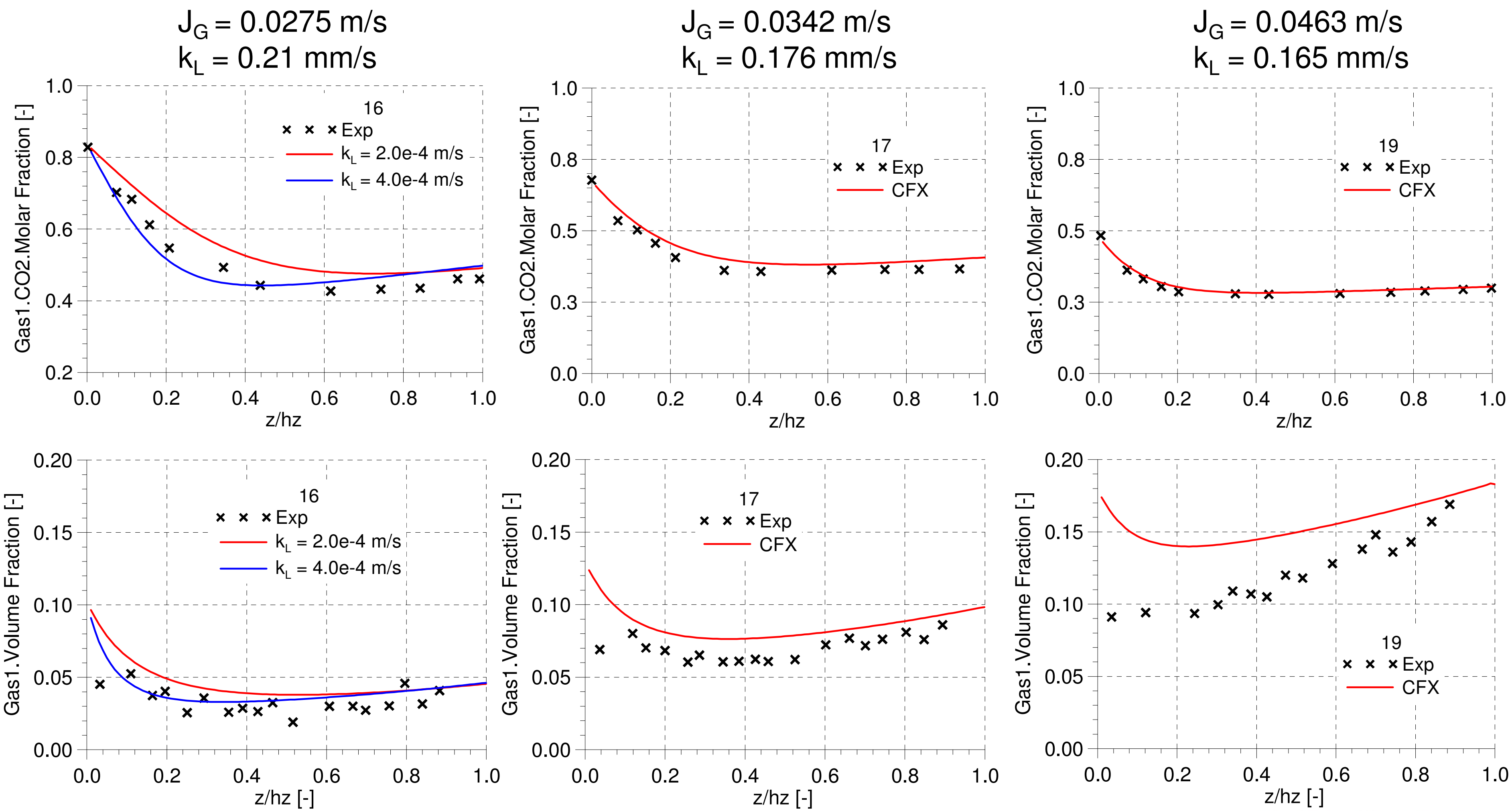


homogeneous distribution over inlet $J_L = 0.0472$ m/s $d_B = 2.9$ mm

Results



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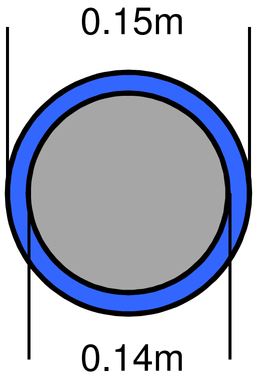
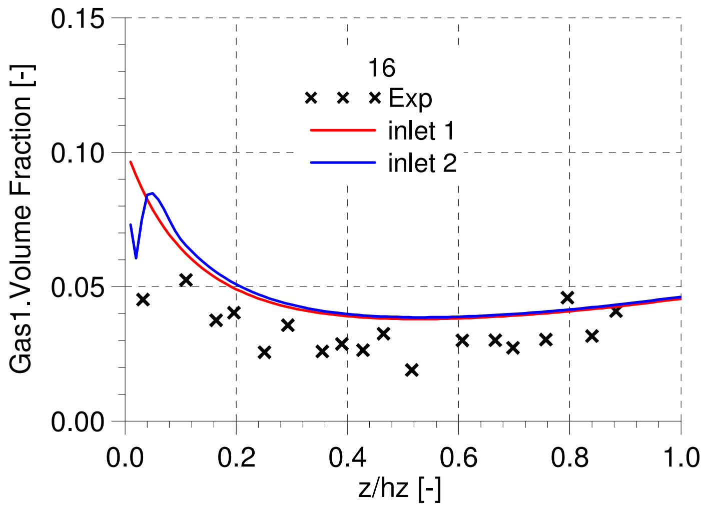
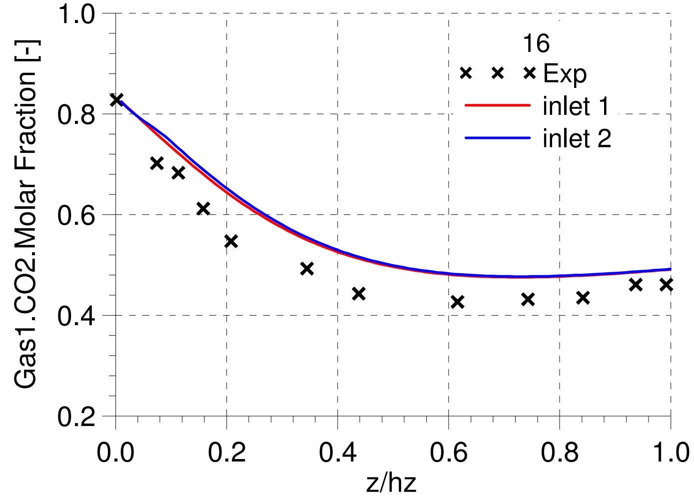
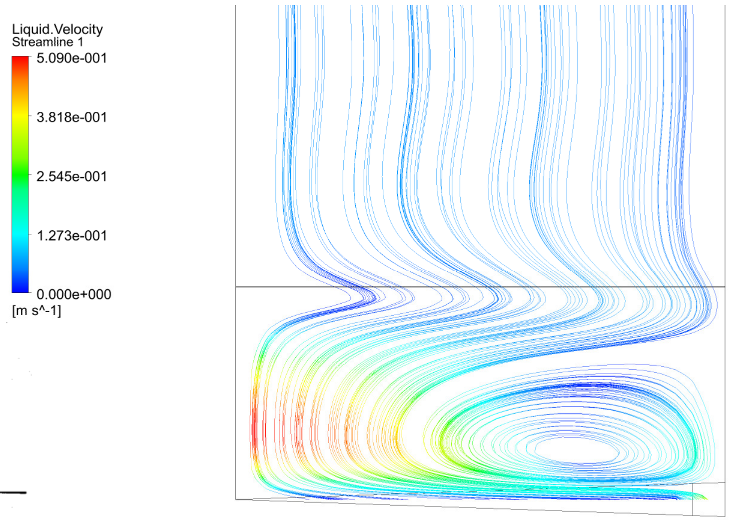


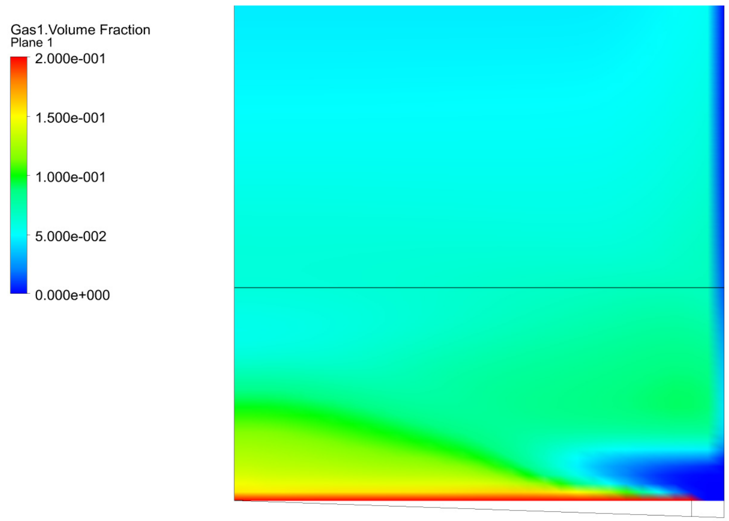
gas inlet
86% of total area

liquid inlet
14% of total area









z / hz ~ 0.1

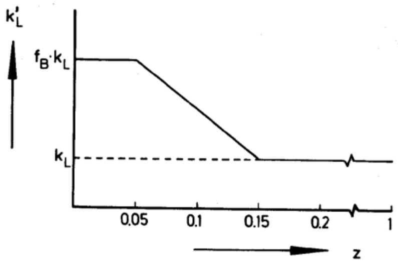
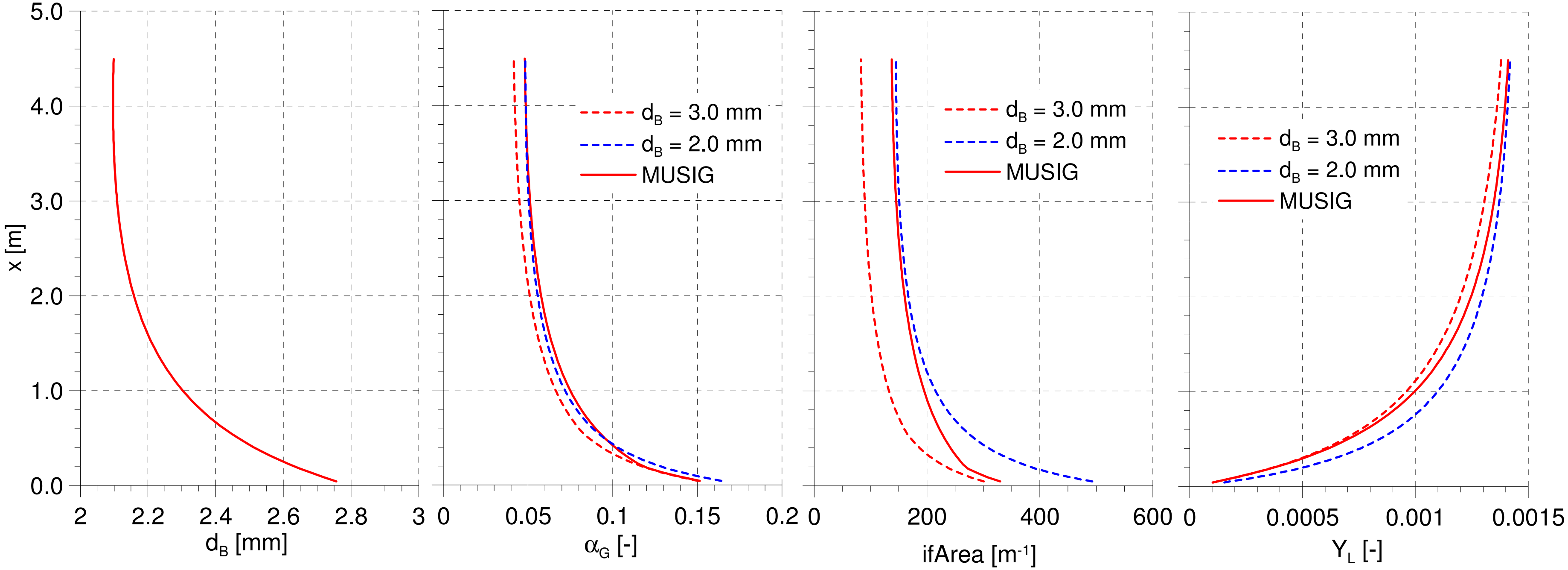


Figure 10 – k_L-profile used in computation, f_B is integer.

With Variable Bubble Size

- inspired by [1978_Deckwer]
- mass transfer coefficient due to Brauer
- fixed bubble size with $d_B = 3$ mm and 2 mm
- variable bubble size by MUSIG model



- awaiting data for validation from partners in SPP 1740

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Summary

established

- baseline approach works for fluid dynamics with fixed polydispersity
- rough quantitative agreement in certain parameter range
- some open issues remain, e.g. suitable inlet modeling
- initial validation for extension to mass-transfer
- model development in progress

ongoing and future work

- promising candidate for bubble coalescence and breakup
- include more complex physics: chemical reaction
- extend to more complex systems: add particles

Thank you for your Attention!

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Reaktive Blasenströmungen
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